The physics of propagating TeV gamma-rays: From plasma instabilities to cosmological structure formation

Christoph Pfrommer[1]

with

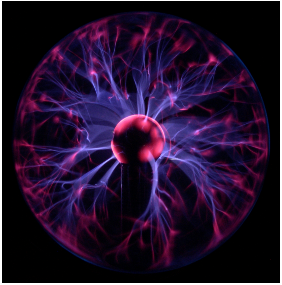
Avery E. Broderick, Phil Chang, Ewald Puchwein, Mohamad Shalaby, Astrid Lamberts, Volker Springel

[1]Heidelberg Institute for Theoretical Studies, Germany

RAPP Center Inauguration meeting, Bochum – 2016

Motivation

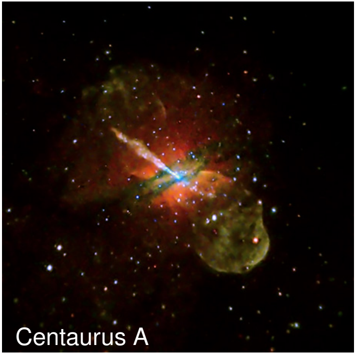
A new link between high-energy astrophysics and cosmological structure formation



- **Introduction to Blazars**
  - active galactic nuclei (AGN)
  - propagating gamma rays
  - plasma physics
- **Cosmological Consequences**
  - unifying blazars with AGN
  - gamma-ray background
  - thermal history of the Universe
  - Lyman-α forest
  - formation of dwarf galaxies

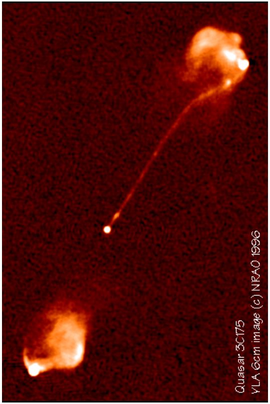
HITS

Active galactic nucleus (AGN)



- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets

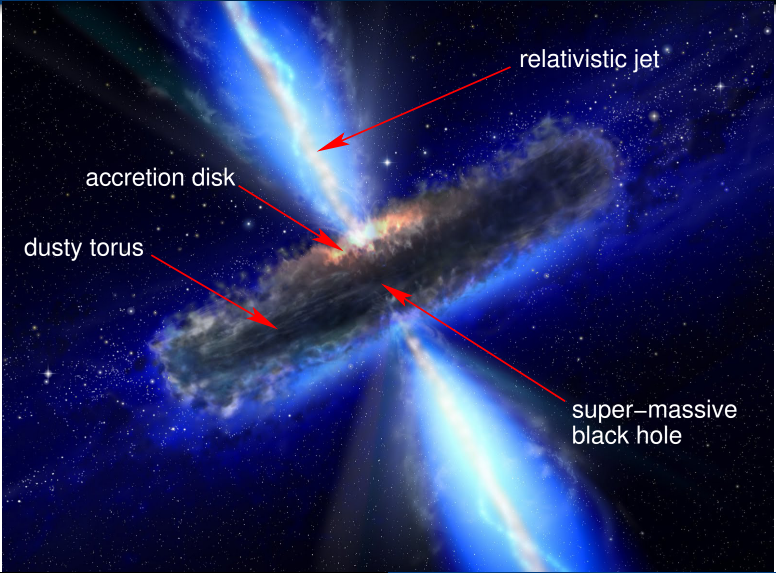
Active galactic nucleus at a cosmological distance



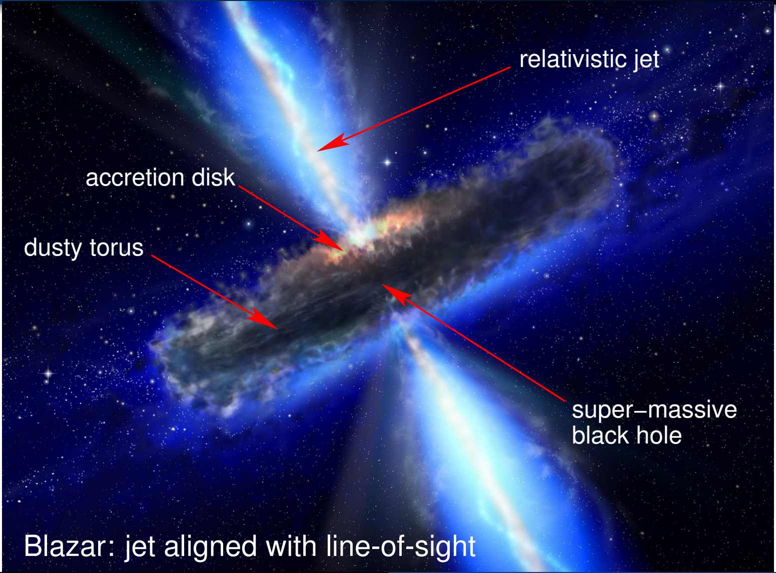
Quasar 3C175 at $z \simeq 0.8$:
jet extends 10^6 light years across

- AGN: compact region at the center of a galaxy, which dominates the luminosity of its electromagnetic spectrum
- AGN emission is most likely caused by mass accretion onto a supermassive black hole and can also launch relativistic jets
- AGNs are among the most luminous sources in the universe $\rightarrow$ discovery of distant objects

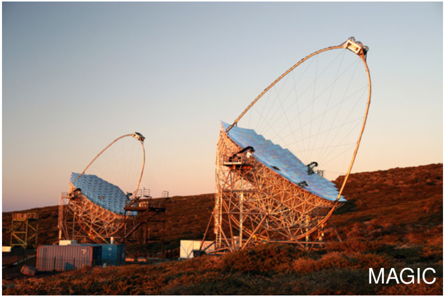
Unified model of active galactic nuclei



Unified model of active galactic nuclei



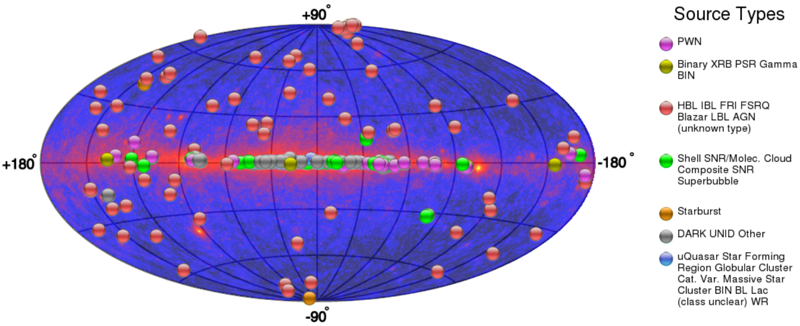
TeV gamma-ray observations



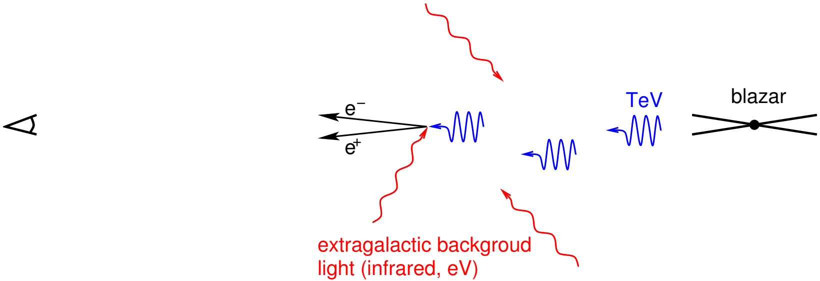
The TeV gamma-ray sky

There are several classes of TeV sources:

- Galactic - pulsars, BH binaries, supernova remnants
- Extragalactic - **mostly** blazars, two starburst galaxies

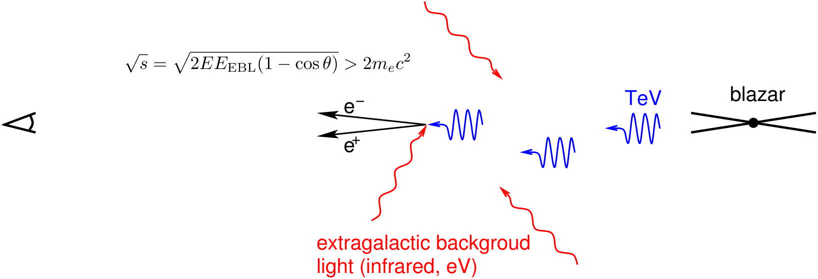


Annihilation and pair production



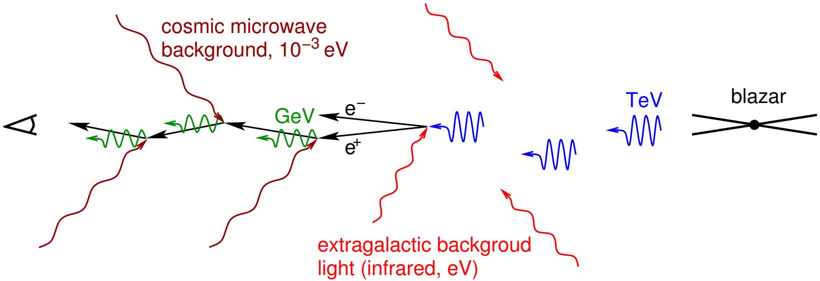
Annihilation and pair production

$$\sqrt{s} = \sqrt{2EE_{\rm EBL}(1-\cos\theta)} > 2m_e c^2$$



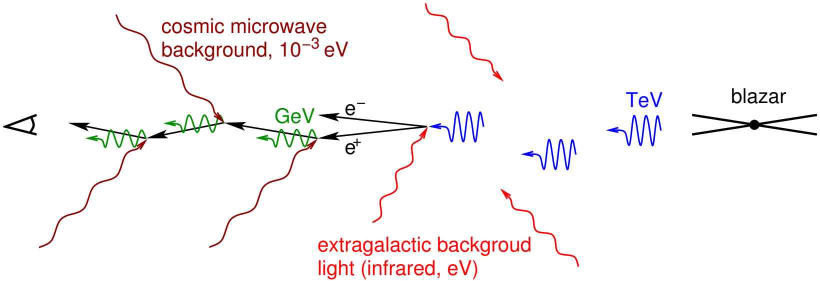
$$\lambda_{\gamma\gamma} \sim (35\ldots700)\ \mathrm{Mpc\ for}\ z = 1\ldots0$$

Inverse Compton cascades



$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$ $\lambda_{\gamma\gamma} \sim (35\ldots700)$ Mpc for $z = 1\ldots0$

Inverse Compton cascades



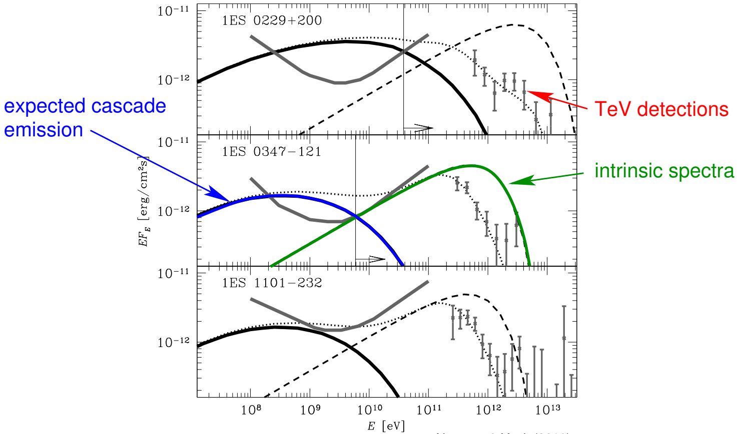
$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$

$\lambda_{\gamma\gamma} \sim (35 \ldots 700)$ Mpc for $z = 1 \ldots 0$

→ each TeV point source should also be a GeV point source!

What about the cascade emission?

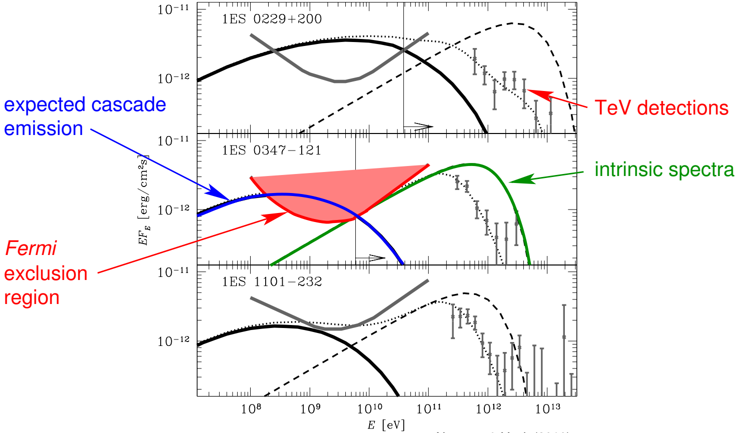
Every TeV source should be associated with a 1-100 GeV gamma-ray halo



Neronov & Vovk (2010)

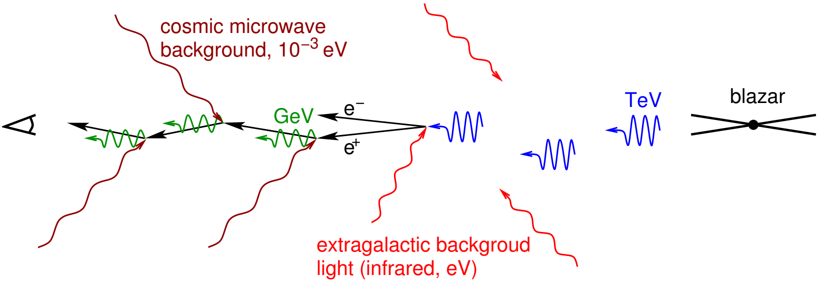
What about the cascade emission?

Every TeV source should be associated with a 1-100 GeV gamma-ray halo – **not seen!**



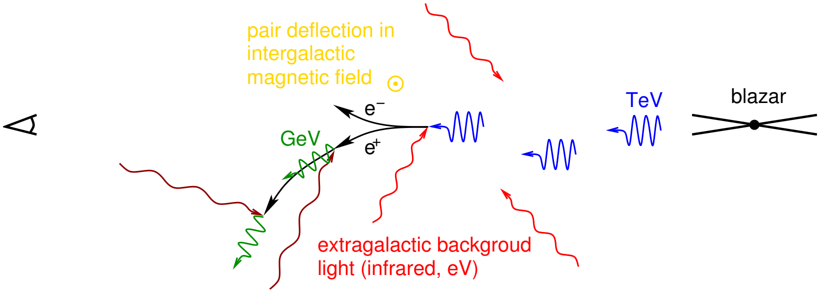
Neronov & Vovk (2010)

Inverse Compton cascades

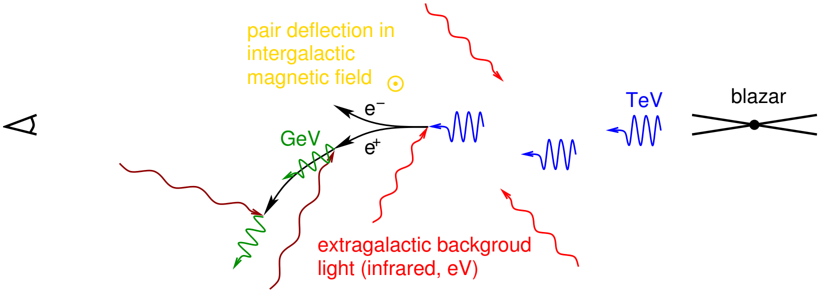


$\lambda_{\mathrm{IC}} \sim \lambda_{\gamma\gamma}/1000$ $\quad$ $\lambda_{\gamma\gamma} \sim (35 \ldots 700)$ Mpc for $z = 1 \ldots 0$

Extragalactic magnetic fields?

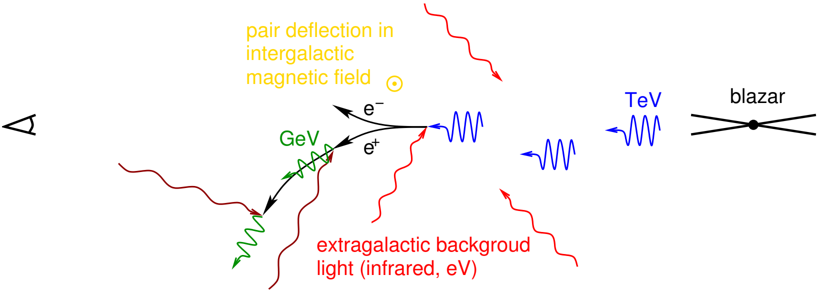


Extragalactic magnetic fields?



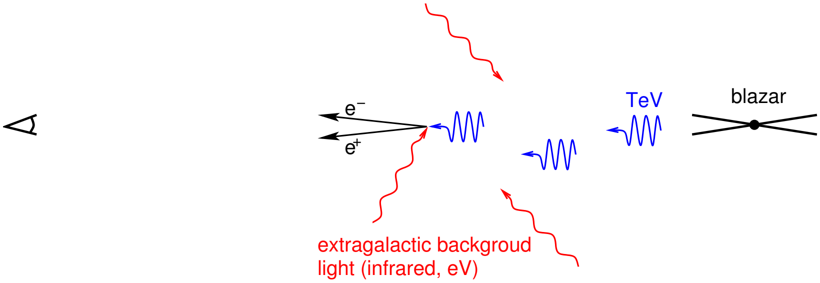
- GeV point source diluted $\longrightarrow$ weak "pair halo"
- stronger B–field implies more deflection and dilution, gamma–ray non–detection $\longrightarrow$ $B \gtrsim 10^{-16}\,\mathrm{G}$ – primordial fields?

Extragalactic magnetic fields?

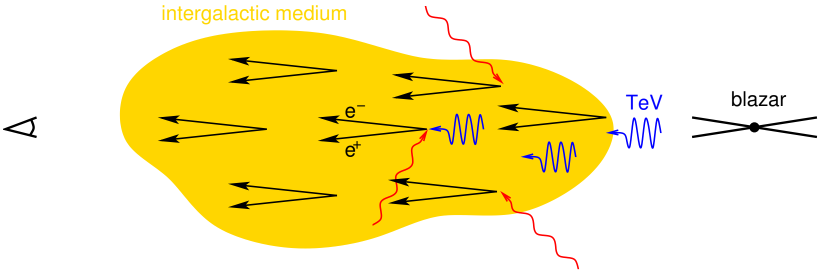


- problem for unified AGN model: no increase in comoving blazar density with redshift allowed (as seen in other AGNs) since other–wise, extragalactic GeV background would be overproduced!

What else could happen?



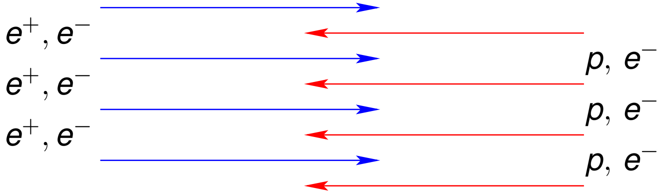
Plasma instabilities



→ pair plasma beam propagating through the intergalactic medium

Plasma instabilities

- pair beam   intergalactic medium (IGM)



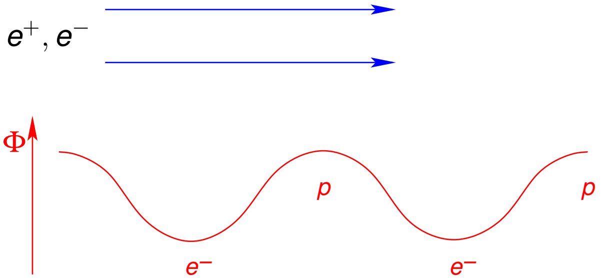
- this configuration is unstable to plasma instabilities
- characteristic frequency and length scale of the problem:

$$\omega_p = \sqrt{\frac{4\pi e^2 n_e}{m_e}}, \qquad \lambda_p = \frac{c}{\omega_p}\bigg|_{\bar{\rho}(z=0)} \sim 10^8\,\mathrm{cm}$$

Two-stream instability

consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):

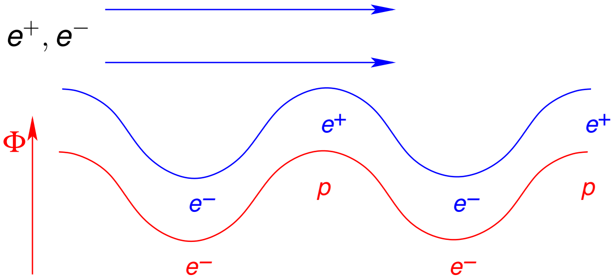
- initially homogeneous beam-e^-:
  attractive (repulsive) force by potential maxima (minima)
- e^- attain lowest velocity in potential minima $\rightarrow$ bunching up
- e^+ attain lowest velocity in potential maxima $\rightarrow$ bunching up



Two-stream instability

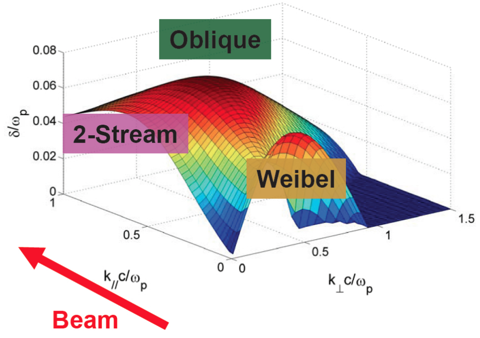
consider wave-like perturbation in background plasma along the beam direction (Langmuir wave):

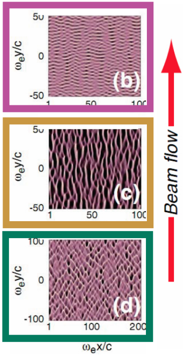
- beam-e^+/e^- couple in phase with the background perturbation: enhances background potential
- stronger forces on beam-e^+/e^- $\rightarrow$ positive feedback
- exponential wave-growth $\rightarrow$ instability



Oblique instability

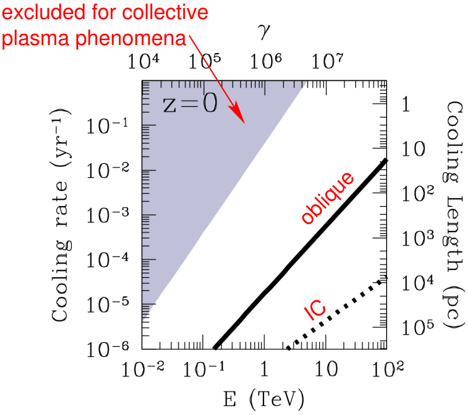
- $\boldsymbol{k}$ oblique to $\boldsymbol{v}_{\rm beam}$: real word perturbations don't choose "easy" alignment $= \sum$ all orientations
- oblique grows faster than two-stream: E-fields can easier deflect ultra-relativistic particles than change their parallel velocities
  (Nakar, Bret & Milosavljevic 2011)





Bret (2009), Bret+ (2010)

Beam physics – growth rates



Broderick, Chang, C.P. (2012), also Schlickeiser+ (2012)

- consider a light beam penetrating into relatively dense plasma
- maximum growth rate

$$\Gamma \simeq 0.4\,\gamma\,\frac{n_{\rm beam}}{n_{\rm IGM}}\,\omega_p$$

- oblique instability beats inverse Compton cooling by factor 10-100
- **assume** that instability grows at *linear* rate up to saturation

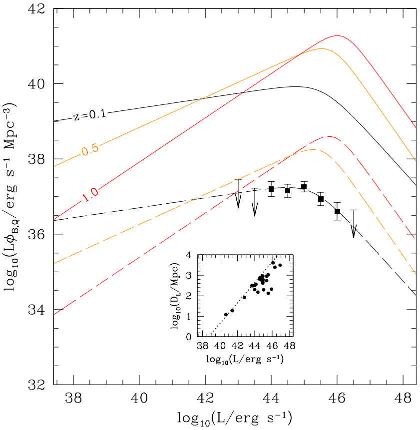
TeV emission from blazars – a new paradigm

$$\gamma_{\mathrm{TeV}} + \gamma_{\mathrm{eV}} \rightarrow e^{+} + e^{-} \rightarrow \begin{cases} \text{inv. Compton cascades} \rightarrow \gamma_{\mathrm{GeV}} \\ \text{plasma instabilities} \end{cases}$$

absence of γ_{GeV}'s has significant implications for ...

- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars

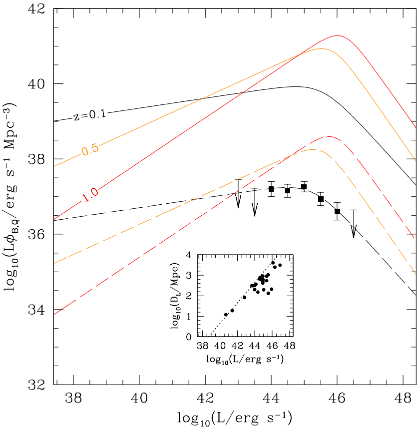
TeV blazar luminosity density: today



Broderick, Chang, C.P. (2012)

- collect luminosity of all 23 TeV blazars with good spectral measurements
- account for the selection effects (sky coverage, duty cycle, galactic occultation, TeV flux limit)
- TeV blazar luminosity density is a scaled version ($\eta_B \sim 0.2\%$) of that of quasars!

Unified TeV blazar-quasar model



Broderick, Chang, C.P. (2012)

Quasars and TeV blazars are:

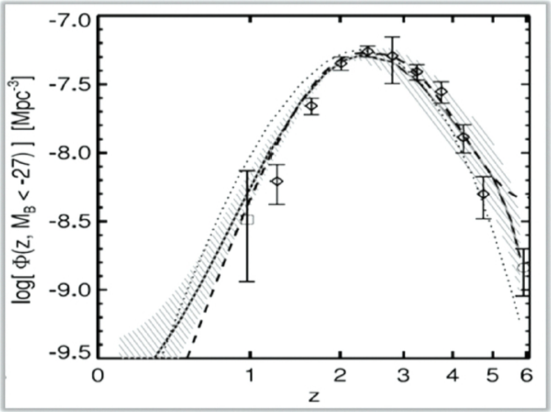
- regulated by the same mechanism
- contemporaneous elements of a single AGN population: TeV-blazar activity does not lag quasar activity

→ **assume that they trace each other for all redshifts!**

How many TeV blazars are there?

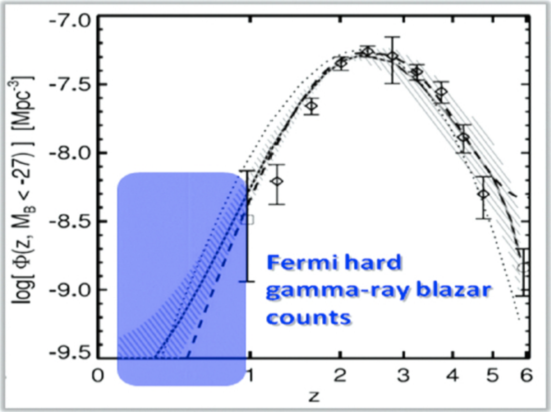
→ use all-sky survey of the GeV gamma-ray sky: *Fermi* gamma-ray space telescope

How many TeV blazars are there?



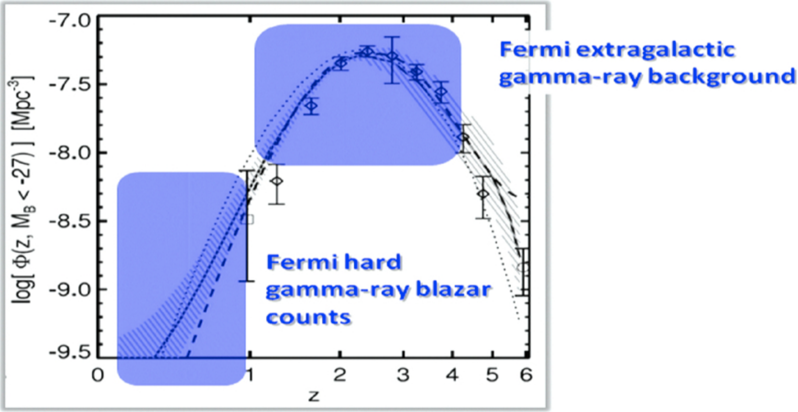
Hopkins+ (2007)

How many TeV blazars are there?



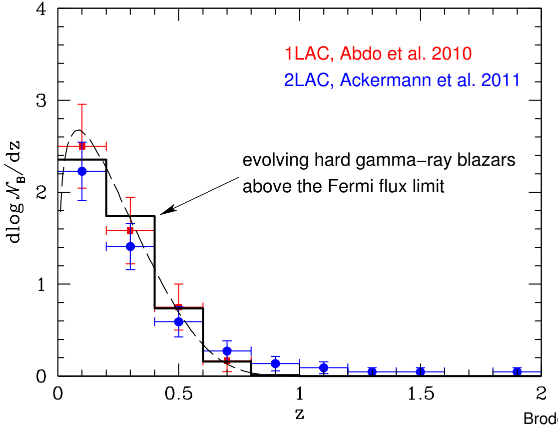
Hopkins+ (2007)

How many TeV blazars are there?



Hopkins+ (2007)

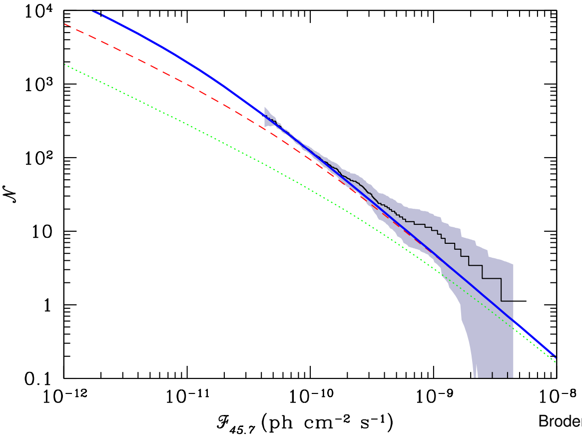
Redshift distribution of *Fermi* hard γ-ray blazars



Broderick, C.P.+ (2013)

→ evolving (increasing) blazar population consistent with observed declining evolution (*Fermi* flux limit)!

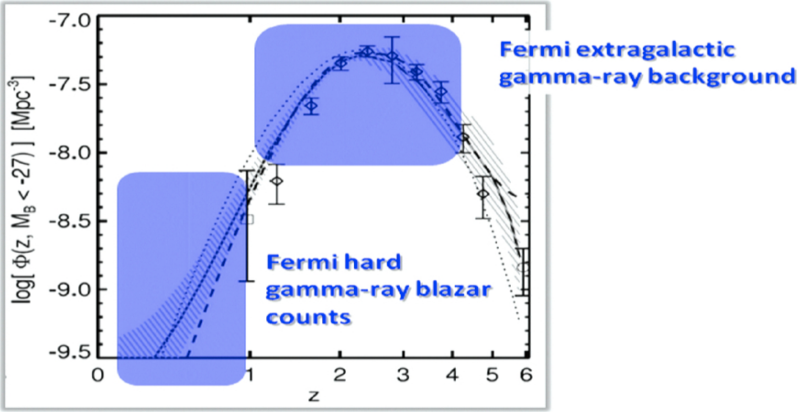
$\log \mathcal{N} - \log S$ distribution of *Fermi* hard γ-ray blazars



Broderick, C.P.+ (2013)

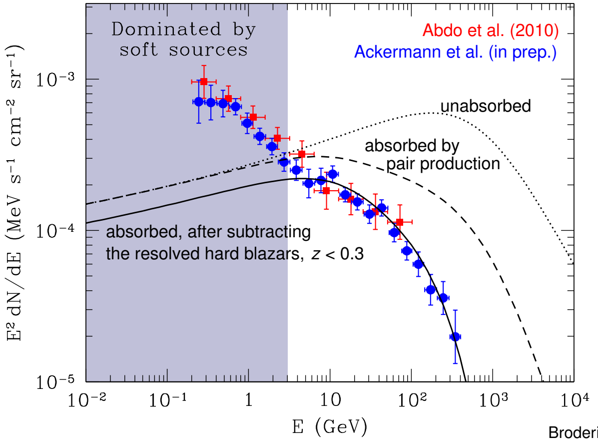
→ predicted and observed flux distributions of hard *Fermi* blazars between 10 GeV and 500 GeV are indistinguishable!

How many TeV blazars are there?



Hopkins+ (2007)

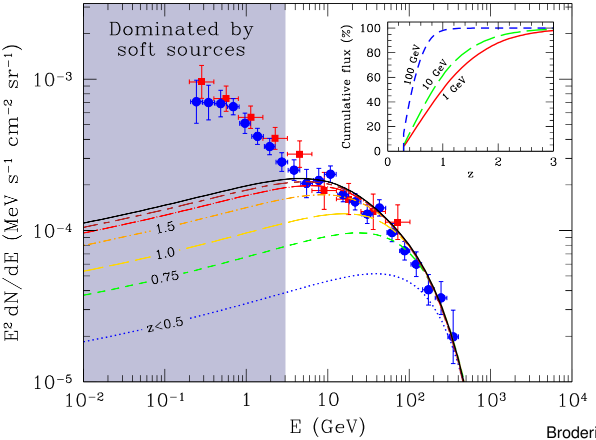
Extragalactic gamma-ray background



Broderick, C.P.+ (2013)

→ evolving population of hard blazars provides excellent match to latest EGRB by *Fermi* for $E \gtrsim 3$ GeV

Extragalactic gamma-ray background



Broderick, C.P.+ (2013)

→ the signal at 10 (100) GeV is dominated by redshifts $z \sim 1.2$ ($z \sim 0.6$)

TeV emission from blazars – a new paradigm

$$\gamma_{\text{TeV}} + \gamma_{\text{eV}} \rightarrow e^+ + e^- \rightarrow \begin{cases} \text{inv. Compton cascades} & \rightarrow \gamma_{\text{GeV}} \\ \text{plasma instabilities} & \rightarrow \text{IGM heating} \end{cases}$$

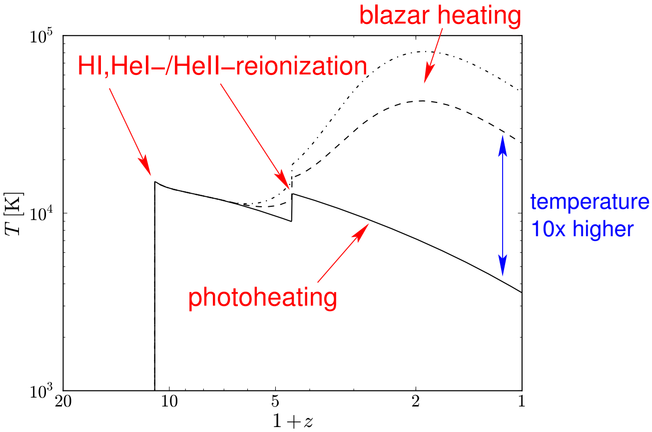
absence of γ_{GeV}'s has significant implications for ...

- intergalactic magnetic field estimates
- unified picture of TeV blazars and quasars:
  explains *Fermi's* γ-ray background and blazar number counts

additional IGM heating has significant implications for ...

- thermal history of the IGM: Lyman-α forest
- late-time formation of dwarf galaxies

Thermal history of the IGM

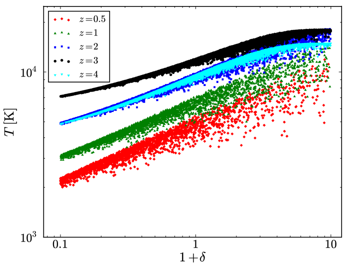


C.P., Chang, Broderick (2012)

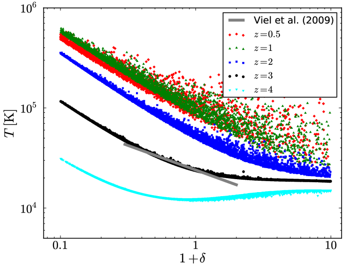
→ increased temperature at **mean** density!

Evolution of the temperature-density relation

no blazar heating



with blazar heating

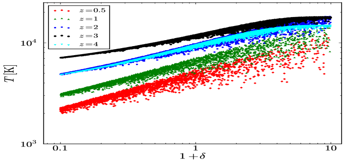


Chang, Broderick, C.P. (2012)

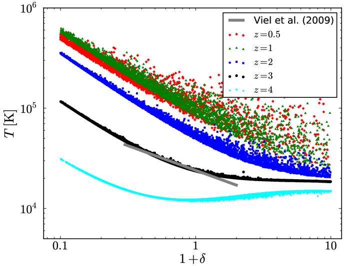
- blazars and extragalactic background light are uniform:
  $\rightarrow$ blazar heating rate independent of density
  $\rightarrow$ makes low density regions *hot*
  $\rightarrow$ causes inverted temperature-density relation, $T \propto 1/\delta$

Blazars cause hot voids

no blazar heating



with blazar heating

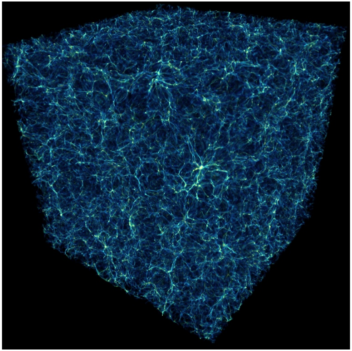


Chang, Broderick, C.P. (2012)

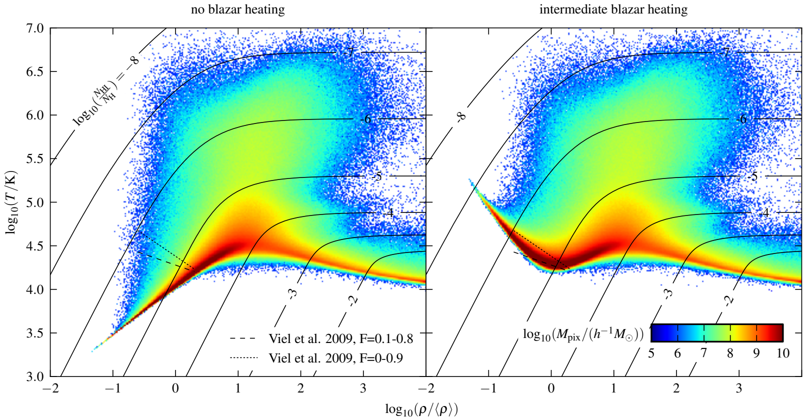
- blazars completely change the thermal history of the diffuse IGM and late-time structure formation

Cosmological hydrodynamical simulations

- include predicted volumetric heating rate in cosmological hydrodynamical simulations
- study:
  - thermal properties of intergalactic medium
  - Lyman-α forest



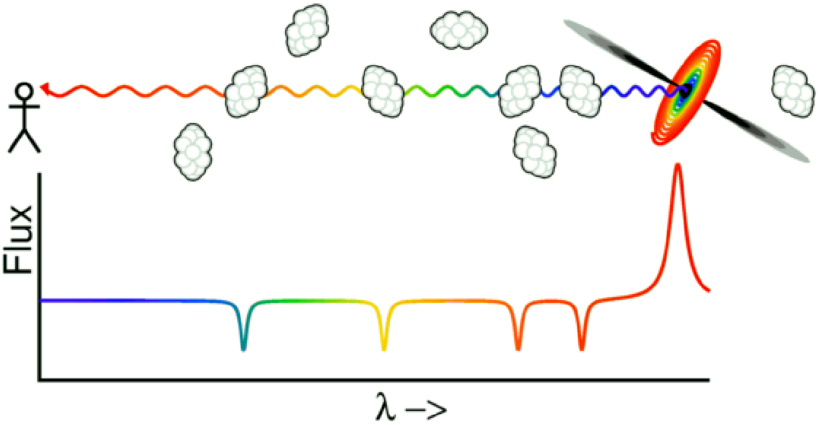
Temperature-density relation



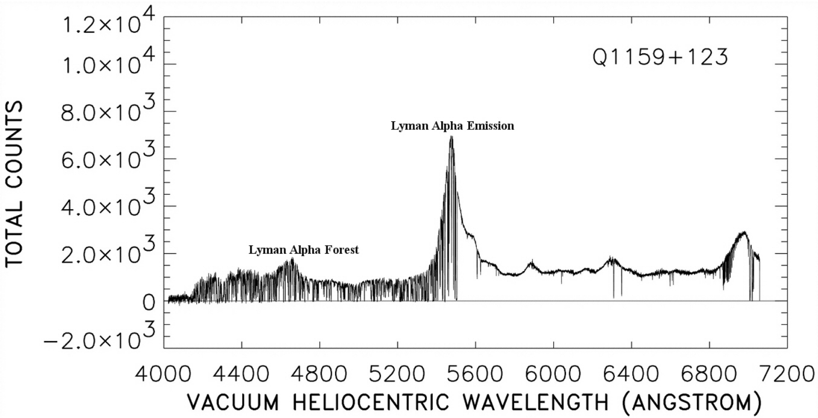
Puchwein, C.P., Springel, Broderick, Chang (2012)

HITS

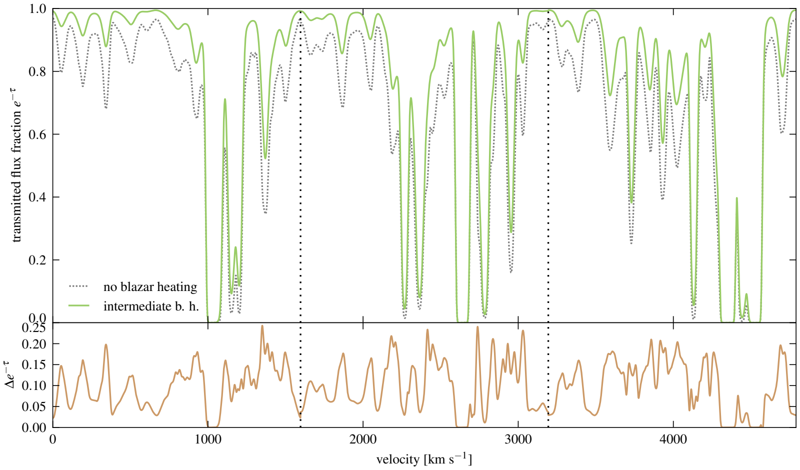
The Lyman-α forest



The observed Lyman-α forest

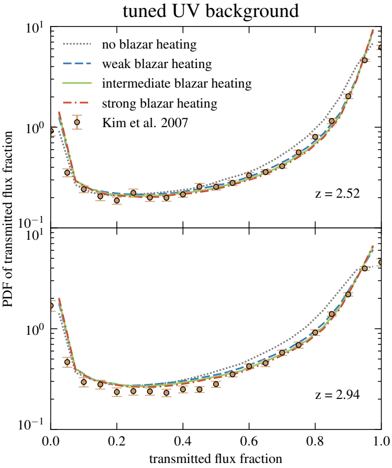


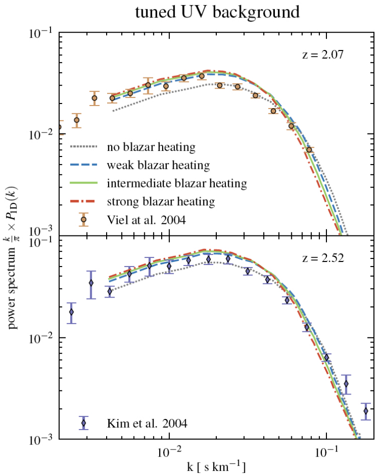
The simulated Ly-α forest



Puchwein, C.P.+ (2012)

Ly-α flux PDFs and power spectra





Puchwein, C.P.+ (2012)

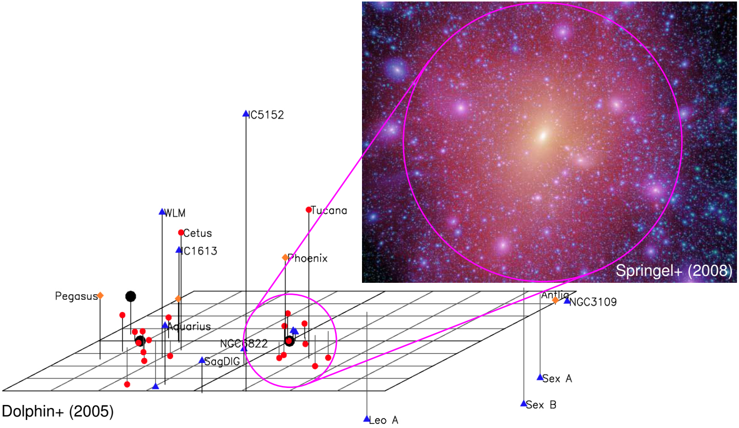
HITS

Lyman-α forest in a blazar heated Universe

improvement in modelling the Lyman-α forest is a direct consequence of the peculiar properties of blazar heating:

- heating rate independent of IGM density $\rightarrow$ naturally produces the inverted T–ρ relation that Lyman-α forest data demand
- recent and continuous nature of the heating is needed to match the redshift evolutions of all Lyman-α forest statistics
- magnitude of the heating rate required by Lyman-α forest data $\sim$ the total energy output of TeV blazars (or equivalently $\sim$ 0.2% of that of quasars)

"Missing satellite" problem in the Milky Way



Dolphin+ (2005)

Substructures in cold DM simulations much more numerous than observed number of Milky Way satellites!

Dwarf galaxy formation

- thermal pressure opposes gravitational collapse on small scales
- characteristic length/mass scale below which objects do not form
- hotter intergalactic medium $\rightarrow$ higher thermal pressure
  $\rightarrow$ higher Jeans mass:

$$M_J \propto \frac{c_s^3}{\rho^{1/2}} \propto \left(\frac{T_{\mathrm{IGM}}^3}{\rho}\right)^{1/2} \quad \rightarrow \quad \frac{M_{J,\mathrm{blazar}}}{M_{J,\mathrm{photo}}} \approx \left(\frac{T_{\mathrm{blazar}}}{T_{\mathrm{photo}}}\right)^{3/2} \gtrsim 30$$

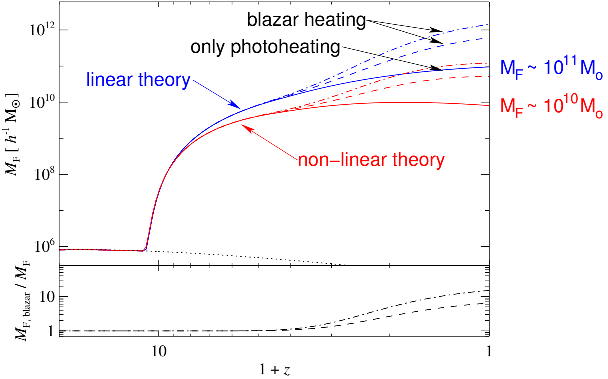
  $\rightarrow$ blazar heating increases M_J by 30 over pure photoheating!

- complications:
  non-linear collapse,
  delayed pressure response in expanding universe $\rightarrow$ concept of "filtering mass"

C.P., Chang, Broderick (2012)

HITS

Dwarf galaxy formation suppressed



C.P., Chang, Broderick (2012)

- blazar heating suppresses the formation of late-forming dwarfs within existing dark matter halos of masses $< 10^{11}$ $M_\odot$
  $\rightarrow$ introduces new time and mass scale to galaxy formation!

Conclusions on blazar heating

Blazar heating: TeV photons are attenuated by EBL; their kinetic energy $\rightarrow$ heating of the IGM; it is *not* cascaded to GeV energies

- explains puzzles in gamma-ray astrophysics:
  - lack of GeV bumps in blazar spectra without IGM *B*-fields
  - *unified TeV blazar-quasar model* explains Fermi source counts and extragalactic gamma-ray background
- novel mechanism; dramatically alters thermal history of the IGM:
  - uniform and *z*-dependent preheating
  - quantitative self-consistent picture of high-*z* Lyman-α forest
- significantly modifies late-time structure formation:
  - suppresses late dwarf formation
  - void phenomenon, "missing satellites" (?)

HITS

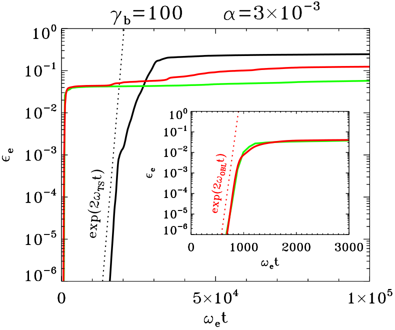
Literature for the talk

- Broderick, Chang, Pfrommer, *The cosmological impact of luminous TeV blazars I: implications of plasma instabilities for the intergalactic magnetic field and extragalactic gamma-ray background*, ApJ, 752, 22, 2012.
- Chang, Broderick, Pfrommer, *The cosmological impact of luminous TeV blazars II: rewriting the thermal history of the intergalactic medium*, ApJ, 752, 23, 2012.
- Pfrommer, Chang, Broderick, *The cosmological impact of luminous TeV blazars III: implications for galaxy clusters and the formation of dwarf galaxies*, ApJ, 752, 24, 2012.
- Puchwein, Pfrommer, Springel, Broderick, Chang, *The Lyman-α forest in a blazar-heated Universe*, MNRAS, 423, 149, 2012.
- Broderick, Pfrommer, Chang, Puchwein, *Implications of plasma beam instabilities for the statistics of the Fermi hard gamma-ray blazars and the origin of the extragalactic gamma-ray background*, ApJ, 790, 137, 2014.
- Chang, Broderick, Pfrommer, Puchwein, Lamberts, Shalaby, *The effect of nonlinear Landau damping on ultrarelativistic beam plasma instabilities*, ApJ, 2014, 797, 110.

Additional slides

Challenges to the Challenge

Challenge #1: **quenching of linear growth & non-linear saturation**



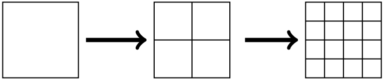
- quenching of linear growth at small level $(10^{-3} - 10^{-2})\ \epsilon_e$
- cold beam: slow secular growth with non-linear saturation only $\sim$ 10% of the beam energy transferred to the IGM

PIC simulations: $\alpha = n_{\text{beam}}/n_{\text{IGM}}$,
1D: black – two-stream & green – oblique,
2D: red – oblique (Sironi & Giannios 2013)

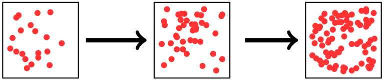
Plasma simulations: resolution

Shalaby+ (2016)

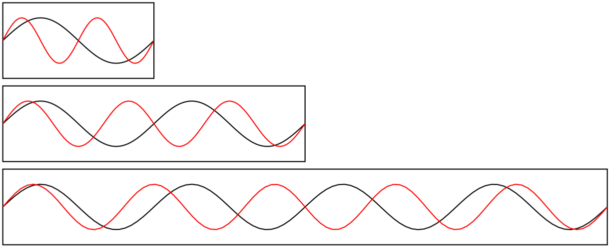
- Spatial resolution:



- Momentum resolution:

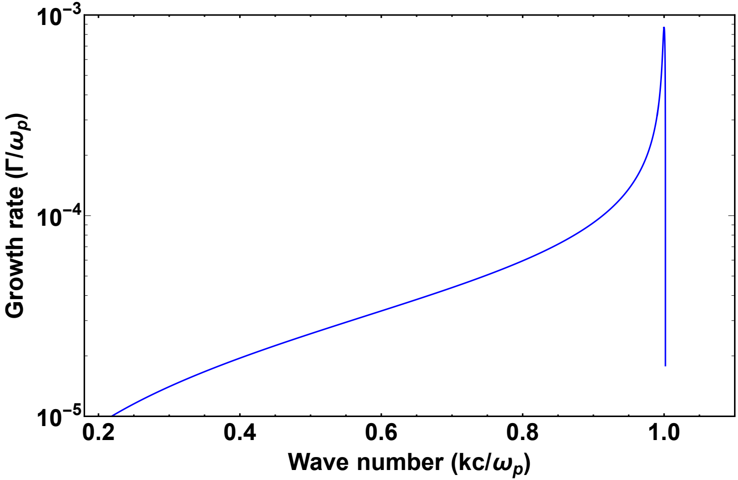


- Spectral resolution:



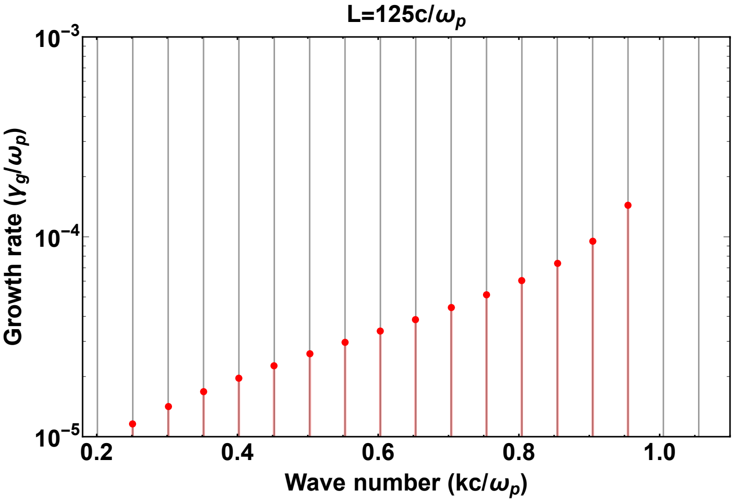
Plasma simulations: resolution

Shalaby+ (2016)



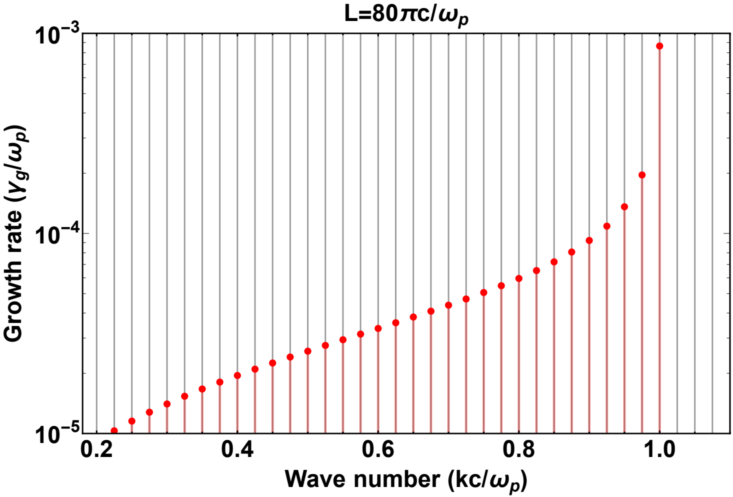
Plasma simulations: resolution

Shalaby+ (2016)



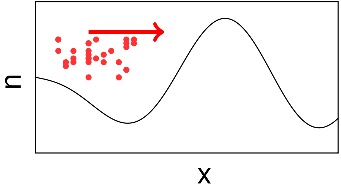
Plasma simulations: resolution

Shalaby+ (2016)



Challenges to the Challenge

Challenge #2: **inhomogeneous universe**



- universe is inhomogeneous $\rightarrow$ electron density changes as a function of position
- could lead to loss of resonance over length scale $\ll$ length scale for instability growth

- condition for linear growth to occur is claimed (Miniati & Elyiv 2013)

$$\frac{\text{few}}{\Gamma_m} < \frac{\Delta k_\parallel}{|dk/dt|} \xrightarrow[\text{modes (1D)}]{\text{electrostatic}} \frac{\gamma_b}{\alpha}\frac{c\lambda_\parallel}{\omega_p} < 1,$$

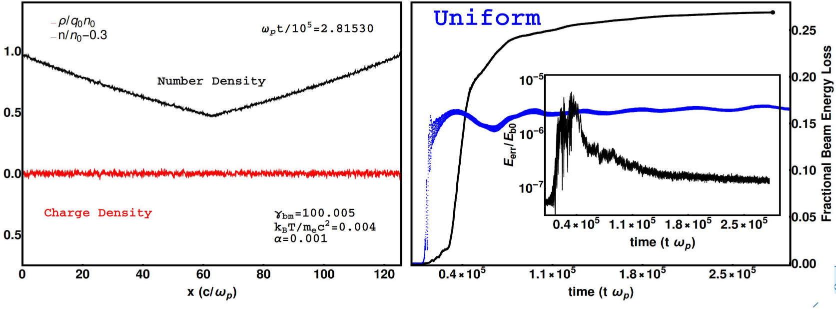
where $\lambda_\parallel \equiv |n/\nabla n|$.

Background inhomogeneity effects

Condition $(\gamma_b/\alpha)\,(c\lambda_{||}/\omega_p) < 1$

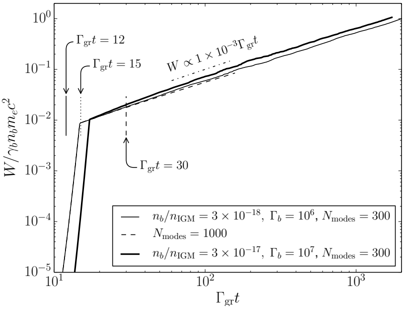
Simulation $(\gamma_b/\alpha)\,(c\lambda_{||}/\omega_p) \sim 10^7$

Shalaby+ (2016): 1D PIC simulation shows linear wave growth at lower growth rate, more energy lost by the beam than for uniform case.



Challenges to the Challenge

Challenge #3: **induced scattering (non-linear Landau damping)**



Chang+ (2014)

- we assume that the non-linear damping rate = linear growth rate
- wave-particle and wave-wave interactions need to be resolved
- using slow *collisional scattering* (reactive regime), Miniati & Elyiv (2012) claim that the nonlinear Landau damping rate is $\ll$ linear growth rate
- accounting for much faster *collisionless scattering* (kinetic regime) $\rightarrow$ **powerful instability, faster than IC cooling**

(Schlickeiser+ 2013, Chang+ 2014)